

Scalar Neutrino as Asymmetric Dark Matter: Radiative Neutrino Mass and Leptogenesis

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Abstract

In the Minimal Supersymmetric Standard Model (MSSM), the scalar neutrino $\tilde{\nu}_L$ has odd R parity, yet it has long been eliminated as a dark-matter candidate because it scatters elastically off nuclei through the Z boson, yielding a cross section many orders of magnitude above the experimental limit. We show how it can be reinstated as a dark-matter candidate by splitting the masses of its real and imaginary parts in an extension of the MSSM with scalar triplets. As a result, radiative Majorana neutrino masses are also generated. In addition, decays of the scalar triplets relate the abundance of this asymmetric dark matter to the baryon asymmetry of the Universe through leptogenesis.

The imposition of R parity, i.e. $R \equiv (-1)^{3B+L+2j}$, in the Minimal Supersymmetric Standard Model (MSSM) of particle interactions serves at least two purposes. One is to avoid proton decay in its renormalizable interactions; the other is to establish a dark-matter candidate which is neutral and stable, i.e. odd under R . This candidate particle may be a boson or a fermion. If it is a boson, then it should be the lightest of three scalar neutrinos $\tilde{\nu}_L$. If it is a fermion, then it should be the lightest of four neutralinos, i.e. the $U(1)$ and neutral $SU(2)$ gauginos and the two neutral higgsinos. However, a scalar neutrino scatters elastically off nuclei with an amplitude mediated by the Z boson, yielding a cross section many orders of magnitude above the present experimental limit, so it was eliminated as a dark-matter candidate many years ago. As for the lightest neutralino, which is a linear combination of gauginos (which do not couple to the Z boson) and higgsinos (which do), it is still considered as the canonical candidate for dark matter.

To reinstate the scalar neutrino as a dark-matter candidate, its elastic scattering with nuclei must be suppressed and this is easily achieved by splitting the mass of its real and imaginary components. The reason is that the coupling of the vector Z boson to $\tilde{\nu}_L = (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2}$ is of the form $Z\tilde{\nu}_1\tilde{\nu}_2$, so if the mass gap is greater than about 100 keV, this process is forbidden by kinematics in the nuclear elastic recoil experiments.

There are now two issues to be considered. (1) How is this splitting achieved? A mass splitting term $\tilde{\nu}_L\tilde{\nu}_L$ cannot be put in by hand, because it is not invariant under the $SU(2)_L \times U(1)_Y$ gauge symmetry of the MSSM. If it is simply assumed to be an effective term without specifying its underlying origin, then it cannot be guaranteed that whatever conclusion is drawn from its existence will not be affected by the actual dynamics which generated it in the first place. Here we assume that it comes from the gauge-invariant term $\Delta_1^0\tilde{\nu}_L\tilde{\nu}_L - \sqrt{2}\Delta_1^+\tilde{\nu}_L\tilde{e}_L - \Delta_1^{++}\tilde{e}_L\tilde{e}_L$, where $\Delta_1 = (\Delta_1^{++}, \Delta_1^+, \Delta_1^0)$ is a scalar triplet, with a vacuum expectation value $\langle\Delta_1^0\rangle = u_1$. (2) Once the specific origin of this splitting is identified,

what are its physical consequences? The first is of course neutrino mass. Since $\tilde{\nu}_L$ carries lepton number L , the induced mass splitting term $\tilde{\nu}_L \tilde{\nu}_L$ breaks L to $(-1)^L$. The observed neutrinos must then have Majorana masses and a radiative contribution must exist through the exchange of $\tilde{\nu}_L$ and neutralinos in one loop. More importantly, the scalar triplet Δ_1 should also couple to the neutrinos directly which then obtain masses through u_1 in the well-known manner of the Type II seesaw. This latter would imply a very small u_1 , much less than 100 keV, thus invalidating the interpretation of $\tilde{\nu}_1$ as dark matter.

In the following we forbid the dimension-four term $\Delta_1^0 \nu_L \nu_L$ by assigning $L = 0$ to $\Delta_{1,2}$ where $\Delta_2 = (\Delta_2^0, \Delta_2^-, \Delta_2^{--})$ and insisting that L be conserved by all dimension-four terms of the supersymmetric Lagrangian of this model. We then break the supersymmetry by soft terms which are allowed to break L to $(-1)^L$ as well, i.e. the dimension-three term $\Delta_1^0 \tilde{\nu}_L \tilde{\nu}_L$. We then show that neutrinos do acquire radiative Majorana masses [1] in this case, but they are only compatible with $\tilde{\nu}_1$ as dark matter if the $U(1)$ and $SU(2)$ gaugino masses have opposite signs, a phenomenological possibility that has been largely overlooked. We also show how the decays of $\Delta_{1,2}$ result [2] in both a lepton asymmetry and an asymmetry in $\tilde{\nu}_L$, with its relic density determined by the subsequent annihilation of $\tilde{\nu}_L \tilde{\nu}_L$ into $\nu_L \nu_L$. Note that the mass splitting of the scalar neutrino is not induced by heavy singlet (right-handed) neutrino superfields through mixing. If it were [3, 4], then there would also be a tree-level neutrino mass from the Type I seesaw. If the inverse seesaw mechanism were used instead [5], then again there would be both a tree-level mass and a loop-induced mass. In our case, only the latter occurs and as we show later in Eq. (3), this is a crucial condition for $\tilde{\nu}_1$ to be a viable dark-matter candidate.

The superpotential of this model is given by

$$\begin{aligned}
W = & \mu \hat{\Phi}_1 \hat{\Phi}_2 + f_{ij}^e \hat{\Phi}_1 \hat{L}_i \hat{e}_j^c + f_{ij}^d \hat{\Phi}_1 \hat{Q}_i \hat{d}_j^c + f_{ij}^u \hat{\Phi}_2 \hat{Q}_i \hat{u}_j^c \\
& + M \hat{\Delta}_1 \hat{\Delta}_2 + f_1 \hat{\Delta}_1 \hat{\Phi}_1 \hat{\Phi}_1 + f_2 \hat{\Delta}_2 \hat{\Phi}_2 \hat{\Phi}_2,
\end{aligned} \tag{1}$$

where $\hat{\Phi}_1 \sim (1, 2, -1/2)$, $\hat{\Phi}_2 \sim (1, 2, 1/2)$, $\hat{L} \sim (1, 2, -1/2)$, $\hat{e}^c \sim (1, 1, 1)$, $\hat{Q} \sim (3, 2, 1/6)$, $\hat{d}^c \sim (3^*, 1, 1/3)$, $\hat{u}^c \sim (3^*, 1, -2/3)$, as in the MSSM. The Higgs triplet superfields are $\hat{\Delta}_1 \sim (1, 3, 1)$ and $\hat{\Delta}_2 \sim (1, 3, -1)$, which have been assigned lepton number $L = 0$, so that the terms $\hat{\Delta}_1 \hat{L}_i \hat{L}_j$ are forbidden.

We allow L to be broken by soft terms which also break the supersymmetry of the model, but only by two units, i.e. $\Delta L = \pm 2$. This would forbid the bilinear $\tilde{L}_i \Phi_2$ and trilinear $\tilde{L}_i \tilde{L}_j \tilde{e}_k^c$, $\tilde{L}_i \tilde{Q}_j \tilde{d}^c$ terms, but allow the trilinear $\Delta_1 \tilde{L}_i \tilde{L}_j$ terms. This pattern is stable because it is maintained by the residual Z_2 symmetry $(-1)^L$. Since $\Delta_{1,2}$ mix through the soft $BM\Delta_1\Delta_2$ term, the two resulting mass eigenstates both decay into states of $L = 2$ as well as $L = 0$, i.e. $\Phi_{1,2}$. Leptogenesis [2] is then possible. Details of this supersymmetric scenario has been worked out previously [6, 7].

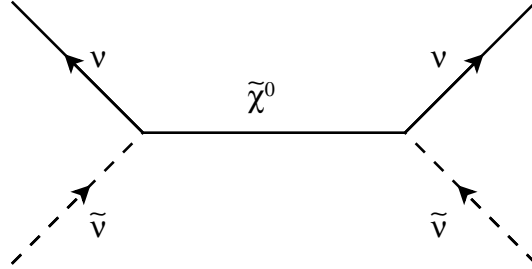


Figure 1: Annihilation of $\tilde{\nu}\tilde{\nu} \rightarrow \nu\nu$ via neutralino exchange.

As a lepton asymmetry is established, there is also an asymmetry of the scalar neutrinos $\tilde{\nu}$. This connection between visible and dark matter has been explored previously [8, 9, 10]. It is also possible in the context of the radiative seesaw model of neutrino mass [1] with the addition of heavy scalar triplets, as proposed recently [11]. As the Universe cools below $m_{\tilde{\nu}}$, the relic abundance of $\tilde{\nu}$ is determined by its annihilation cross sections with itself and with $\tilde{\nu}^*$. The latter is very large, which means it contributes very little to the $\tilde{\nu}$ relic abundance. The former is rather small, so its would-be relic density may be very large, but it is diminished by the $\tilde{\nu} - \tilde{\nu}^*$ asymmetry created earlier, so it may be just right. In that

case, it would be a good candidate for the dark matter of the Universe. The $\tilde{\nu}\tilde{\nu}$ annihilation proceeds through neutralino exchange, as shown in Fig. 1. In the 4×4 neutralino mass matrix, if the higgsino mass parameter μ is large, then the 2×2 gaugino mass matrix does not mix significantly with the 2×2 higgsino mass matrix, resulting in approximate mass eigenvalues $m_{1,2}$ for the $U(1)$ and $SU(2)$ gauginos. In that case, this cross section \times relative velocity is given by

$$\langle\sigma v\rangle = \frac{g^4}{128\pi c^4 m_{\tilde{\nu}}^2} \left(\frac{s^2 y_1}{y_1^2 + 1} + \frac{c^2 y_2}{y_2^2 + 1} \right)^2, \quad (2)$$

where $s = \sin \theta_W$, $c = \cos \theta_W$, and $y_{1,2} = m_{1,2}/m_{\tilde{\nu}}$.

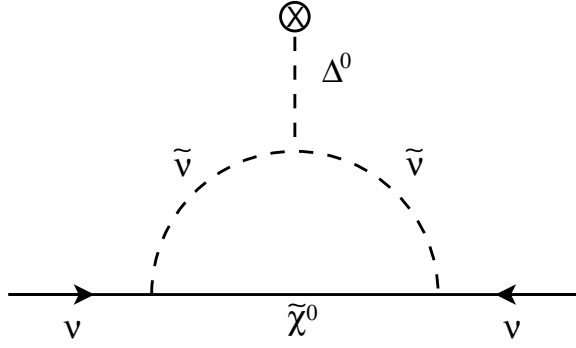


Figure 2: One-loop radiative Majorana neutrino mass via neutralino exchange. Lepton number L becomes $(-1)^L$ through the soft $\Delta^0 \tilde{\nu}\tilde{\nu}$ term.

For each $\tilde{\nu}$, a radiative neutrino mass is also generated in one loop by neutralino exchange, as shown in Fig. 2, resulting in [1, 3]

$$\frac{m_\nu}{\Delta m_{\tilde{\nu}}} = \frac{g^2}{32\pi^2 c^2} \left[\frac{s^2 y_1}{y_1^2 - 1} \left(1 - \frac{y_1^2}{y_1^2 - 1} \ln y_1^2 \right) + \frac{c^2 y_2}{y_2^2 - 1} \left(1 - \frac{y_2^2}{y_2^2 - 1} \ln y_2^2 \right) \right]. \quad (3)$$

Since $\Delta m_{\tilde{\nu}} > 100$ keV is needed to suppress the interaction of $\tilde{\nu}_1$ with nuclei in underground direct-search experiments, and $m_\nu < 1$ eV for neutrino mass, the above ratio should be less than 10^{-5} . We assume that $|y_2| > |y_1| > 1$ and plot y_2 as a function of $-y_1$ so that $m_\nu/\Delta m_{\tilde{\nu}} = 0$ in Fig. 3. We also use Eq. (2) to plot $m_{\tilde{\nu}}$ as a function of $-y_1$ for the particular value of $\langle\sigma v\rangle = 0.1$ pb. This value is an order-of-magnitude smaller than the benchmark

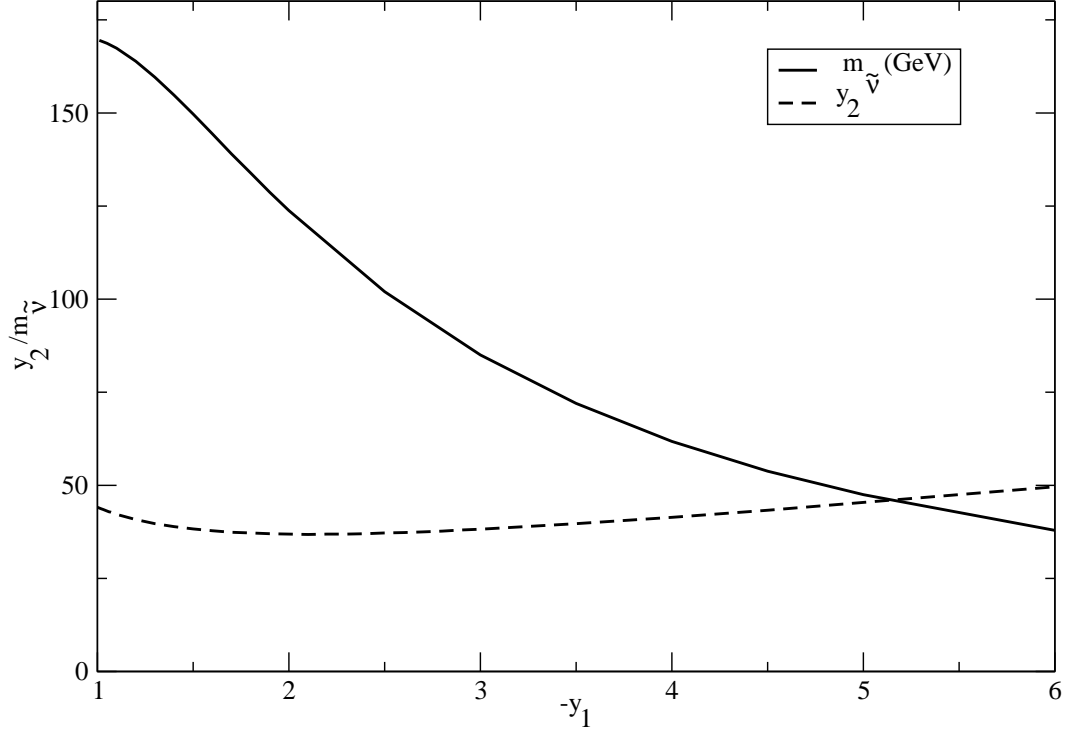


Figure 3: y_2 and $m_{\tilde{\nu}}$ are plotted against $-y_1$, which correspond to $m_{\nu}/\Delta m_{\tilde{\nu}} = 0$ and $\langle\sigma v\rangle = 0.1$ pb.

value of 1 pb for usual dark matter, and would overclose the Universe in that case. Here, because of the $\tilde{\nu}$ asymmetry, the resulting relic density will be reduced and possible agreement with observation may be obtained. Details will depend on other unknown parameters. We simply use 0.1 pb to indicate the possible range of $m_{\tilde{\nu}}$ values in this scenario. We note that $m_{\tilde{\nu}} < m_Z/2$ is ruled out experimentally, because $Z \rightarrow \tilde{\nu}_1 \tilde{\nu}_2$ would then contribute to its invisible width, which already agrees very well with what is expected from the three known neutrinos of the Standard Model.

In underground dark-matter direct-search experiments, the spin-independent elastic cross section for $\tilde{\nu}_1$ scattering off a nucleus of Z protons and $A - Z$ neutrons normalized to one

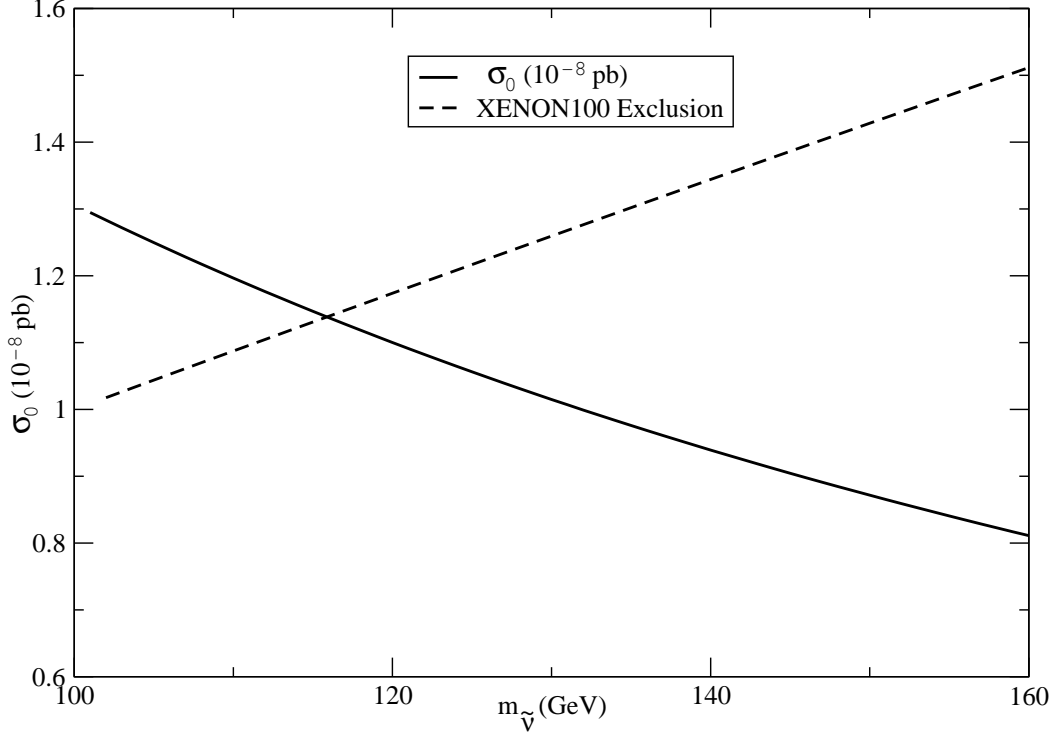


Figure 4: Spin-independent elastic scattering cross section of $\tilde{\nu}_1$ with ^{131}Xe through Higgs exchange is plotted together with the present experimental bound from the direct-search experiment XENON100, as a function of $m_{\tilde{\nu}}$.

nucleon is given by

$$\sigma_0 = \frac{1}{\pi} \left(\frac{m_N}{m_{\tilde{\nu}} + Am_N} \right)^2 \left| \frac{Zf_p + (A-Z)f_n}{A} \right|^2, \quad (4)$$

where m_N is the mass of a nucleon, and $f_{p,n}$ come from Higgs exchange [12]:

$$\frac{f_p}{m_p} = \left(-\frac{0.075}{4} - \frac{0.925(3.51)}{54} \right) \frac{g^2}{c^2 m_\phi^2}, \quad (5)$$

$$\frac{f_n}{m_n} = \left(-\frac{0.078}{4} - \frac{0.922(3.51)}{54} \right) \frac{g^2}{c^2 m_\phi^2}. \quad (6)$$

Assuming an effective $m_\phi = 130$ GeV and using $Z = 54$ and $A - Z = 77$ for ^{131}Xe , we plot σ_0 as a function of $m_{\tilde{\nu}}$ in Fig. 4. Note for $m_{\tilde{\nu}} = 120$ GeV, $\sigma_0 = 1.1 \times 10^{-8}$ pb, which is just below the upper limit of the 2011 XENON100 exclusion [13]. The allowed range for $m_{\tilde{\nu}}$ is thus above 116 GeV and probably no greater than about 170 GeV from Fig. 3.

If $\Delta m_{\tilde{\nu}} < 2m_e$, the decay of $\tilde{\nu}_2$ is only to $\tilde{\nu}_1 \nu \bar{\nu}$ through Z exchange. This decay width is given by

$$\Gamma(\tilde{\nu}_2 \rightarrow \tilde{\nu}_1 \nu \bar{\nu}) = \frac{G_F^2 (\Delta m_{\tilde{\nu}})^5}{60\pi^3}. \quad (7)$$

For $100 \text{ keV} < \Delta m_{\tilde{\nu}} < 1 \text{ MeV}$, the corresponding lifetime is of order 10^9 to 10^4 seconds. This means that in the early Universe, $\tilde{\nu}_L \tilde{\nu}_L$ annihilation should be considered for determining the relic abundance of $\tilde{\nu}_L$, but at present only $\tilde{\nu}_1$ survives as dark matter. If a concentration of $\tilde{\nu}_1$ has accumulated inside the sun or the earth, $\tilde{\nu}_1 \tilde{\nu}_1$ annihilation to two monoenergetic neutrinos [14] would be a spectacular indication of this scenario.

If $\tilde{\nu}_1$ is dark matter, its production at the Large Hadron Collider (LHC) must always be accompanied by a lepton. If it comes from the decay of the $U(1)$ gaugino, i.e. $\tilde{B} \rightarrow \bar{\nu} \tilde{\nu}$, then it is completely invisible. If it comes from a chargino, i.e. $\tilde{\chi}^+ \rightarrow e^+ \tilde{\nu}$, then it may be discovered through its missing energy and large mass. More detailed study of this scenario is required.

The Higgs triplet scalars $\Delta_{1,2}$ are the common origins of both the observed baryon asymmetry and the asymmetric $\tilde{\nu}_L$ dark matter of the Universe. They are likely to be very heavy, say of order 10^8 GeV , in which case they are not accessible at the LHC. On the other hand, resonant leptogenesis may occur naturally in this scenario [7], which would allow them to be at the TeV scale. In that case, the direct decay $\Delta_1^{++} \rightarrow \tilde{e}_i^+ \tilde{e}_j^+$ would serve to map out the neutrino mass matrix, in analogy to the previously proposed simple scenario [15, 16], where $\Delta^{++} \rightarrow e_i^+ e_j^+$.

In conclusion, we have proposed that the dark matter of the Universe is the real component of the lightest scalar neutrino $\tilde{\nu}_1$ in the Minimal Supersymmetric Standard Model. To implement this unconventional scenario, we add Higgs triplet superfields $\hat{\Delta}_{1,2}$, so that the observed neutrinos acquire small radiative Majorana masses from the mass splitting terms $\Delta_1 \tilde{\nu}_L \tilde{\nu}_L$. The fact that $m_\nu / \Delta m_{\tilde{\nu}} < 10^{-5}$ forces the $U(1)$ and $SU(2)$ gaugino masses to

have opposite signs. Using the canonical 1 pb cross section for dark matter and the latest XENON100 data, the allowed mass range of $\tilde{\nu}_1$ is above 116 GeV and probably no greater than about 170 GeV, assuming a Higgs-boson mass of 130 GeV.

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